Report of the C-AD Machine Advisory Committee Meeting

2-4 November 2011

1. Executive Summary

The committee compliments the RHIC team for their excellent accomplishments during the last year. The luminosity runs were very successful; for gold collisions the expectations were significantly exceeded, and also for the proton run almost all expectations were met, except for the integrated luminosity, which suffered from several unforeseeable technical faults.

We are also very pleased to see that the C-AD team has taken previous recommendations very seriously, has responded to nearly all recommendations and provided updates and showed results of the recommended studies. We have taken this as an effective encouragement for thorough advisory-committee work.

Important improvements since the last meeting of the C-AD MAC have led to an increase in luminosity and proton polarization. Particularly a horizontal realignment in the AGS and more precise tune jumps led to much better optic functions and higher polarization from the AGS into RHIC, and technical improvements in the final focus led to a reduced beta* at the interaction points. Several feedback systems have significantly improved the beam stability leading to more stable operation and better operation parameters. For example, the ability to control RHIC closer to the 2/3 resonance has increased the polarization levels of the proton beams. These improvements will be very valuable when operating very close to the beam-beam limit with the new experiment AnDY.

Detailed studies have led to an increased understanding of the C-AD accelerator complex, particularly in RHIC. For instance, the understanding of the dynamic aperture and beam losses and the polarization dynamics has much improved. However, some significant questions still remain, such as beam loss at the start of colliding-beam operation and the quantitative understanding of the polarization lifetime at high energy.

The next run will see for the first time uranium-uranium collisions in RHIC. The success with previous proton, gold, and copper runs give confidence that the uranium run will also perform well. Nevertheless, below we suggest studies and technology considerations that we hope will help at several places in the accelerator chain. Because RHIC appears to have been studied with more sophistication than the lower energy chain, it seems to be better equipped with diagnostics tools and to receive more attention in terms of manpower, several of our suggestions refer to the pre-accelerators of the RHIC complex.

A list of promising upgrades that are to be implemented over the next several years has been developed, including those discussed in more detail in this report.

2. RHIC latest performance and upgrade

2.1. Findings

RHIC achieved an impressive performance record during the 2011 run. The intensity and time averaged proton polarization exceeded with 48% the Run-9 performance levels and reached the upper end of the Run-11 performance projections. Similarly good figures have been achieved for the peak and average luminosity levels and the integrated luminosity per week clearly exceeded the Run-9 performance levels and lies well within the Run-11 projections. However, due to three major technical problems (AGS power failure, RHIC cryogenic failure and failure of the 9 MHz RF system) the total integrated luminosity for the 2011 proton run falls short of the minimum projected performance estimates.

The list of polarization improvements along the accelerator chain for the Run-11 is impressive and the achieved record polarization at the end of the ramp in RHIC at 250 GeV was in 2011 above 50%. The improvements in the beam controls (orbit, tune, Q' and coupling feedback) and machine understanding (e.g. operation with increased magnet currents) are also impressive and put the machine well on track for a future operation near the integer tune that could provide even further improvements to the polarization levels in RHIC. The high level of machine understanding and beam control is well illustrated by the polarization studies featuring ramp-up and ramp-down cycles with beam.

First operational experience with an additional experiment in IP2 have clearly underlined that RHIC is running close to its beam-beam limit. Operation with the additional experiment AnDY might therefore impose limits on the total beam brightness and limit the peak performance for the main RHIC experiments STAR and PHENIX.

Future plans for the polarized proton operation in RHIC feature an exhaustive list of additional upgrade plans (e.g. new H- source and electron lens for beam-beam compensation) aiming at a further performance increase (three fold increase in average luminosity and 70% polarization) over the coming years (by 2014), and even higher performance gains in the long run (requiring additional measures). The studies related to a new H- source and the electron lens for compensating the head-on beam-beam effect are well advanced and on track for the upgrade goals by 2014.

The RHIC performance with heavy ion operation also surpassed the performance levels of the previous years in terms of integrated luminosity per week and even exceeded the maximum Run-11 projections. A key ingredient for the successful heavy ion operation is the stochastic cooling system, which was used in the longitudinal and vertical planes and provided a factor 2 increase in integrated luminosity. A further upgrade of the cooling system (additional cooling in the horizontal plane) is planned for the 2012 run period and might further boost the RHIC performance for heavy ion operation.

The development of the new EBIS ion source provides room for additional performance improvements and more flexibility in terms of ion species for future operation periods.

2.2. Comments

The list of achieved and planned upgrade projects is impressive and puts RHIC on a good track for continuing its excellent performance track record. The future ion beam operation with a new superconducting RF system will increase the momentum spread in the beam which might in turn degrade the machine performance due to a reduced off-momentum dynamic aperture. While the list of future upgrade plans for RHIC is impressive, the committee was under the impression that the RHIC injector complex (AGS and Booster) did not receive the same level of attention.

2.3. Recommendation

- Evaluate (experimentally and by simulations) precisely the maximum acceptable beam-beam parameter for operation with AnDY. Estimate the impact for operation with AnDY.
- Prepare by the next review a detailed list of potential upgrades and improvements of the RHIC injection complex and evaluate them on the base of projected integrated luminosity gains, required resources and technical challenges.

3. Polarized source upgrade

3.1. Findings

Atomic H injector produces an order of magnitude higher brightness beam than present ECR source. A 5-10mA polarized H^- ion current can be obtained for the smaller (higher brightness) beam with polarization 85-90%. The resulting polarized proton beam promises to be 10 times in intensity and 5-8% increased in polarization.

The superconducting magnetic coil delivery is delayed since the solenoid needed rework to reach the design field, and has delayed the installation by 12 month, now planned for the summer of 2012, after the Run-12 end. This may delay the whole project completion, and the possibility of commissioning both the new solenoid and the Atomic Beam Source at the same time is now being studied.

3.2. Comments

Besides the delay in the superconducting solenoid delivery, the project is making good progresses in this high polarization and high intensity beam polarized ion source project.

This project can also provide information on the basic limitation on the production of the high-intensity (>100mA), high-brightness un-polarized H^- ion beam.

There is an upgrade to re-design the 200MeV polarimeter. It would be very useful to measure both the polarization profile and beam distribution profile. This combined data can be useful in detailed analysis of polarization loss.

3.3. Recommendation

- Make sure that the new solenoid design does not fall onto the same flaw as that of earlier design and manufacturing process.
- Measure the beam emittance and polarization profile at the end of the linac.

4. High intensity protons in the Booster and AGS

4.1. Findings

The AGS operates as RHIC polarized proton injector with two partial snakes and two horizontal tune jump quadrupoles. It has delivered a proton beam with 65-70% polarization and $1.7*10^{11}$/bunch intensity for 80% as input polarization.

The AGS tune-jump quadrupoles increase the polarization by 5% to about 65-70%, up from about 60-65%, representing a relative gain of 8%. There are 82 tune jumps during AGS acceleration. The jump quadrupoles have a significant effect on the horizontal polarization profile, rendering the profile almost flat horizontally, while a noticeable amplitude dependence still remains in the vertical profile.

The polarization measured in the AGS at top energy shows a decrease as a function of intensity. This is partly explained by the fact that higher intensity comes with larger emittance at top energy (28 GeV), and partly attributed to a systematic intensity dependent error of the polarimeter. Simply extrapolating the observed slope the expected polarization from the AGS would be only 54% at 3e11 protons per bunch, down from 77% at zero intensity. It was reported that at AGS injection there is little dependence of polarization on intensity. An upgrade of the polarimeter is planned, which should remove the intensity dependence of the measurement.

The new proton source will provide a 1.65 times higher bunch intensity for about the same (and maybe slightly smaller) emittance. If the polarization loss is solely due to the emittance it should stay the same at the higher intensity.

The intensity transmission from the entrance of the booster to AGS extraction is about 50%. In addition there is about a factor 2 emittance growth in the AGS for both transverse planes, at 2e11 particles per bunch. There is strong evidence that this emittance growth occurs directly at or near injection. The prime candidate mechanism for explaining this emittance growth (and also a large part of the intensity loss in the AGS) is an optical mismatch. Optical matching at injection is not satisfactory at the moment, because there is no realistic optics model and due to the absence of the necessary diagnostics. A ZGOUBI model with stable orbit is under construction.

The AGS accommodates no turn-by-turn emittance measurements, which would allow empirical matching. There do exist a few turn-by-turn BPMs which permit steering and minimization of injection oscillations.

The present space-charge (SC) tune shifts at injection are -0.077 and -0.116 in the two transverse planes. With the source upgrade these numbers could increase by a factor 1.65 to 2.0, and SC effects could then become important. To mitigate SC effects, if needed, the RF harmonic number can be reduced, from 12 to 6. A test with the lower harmonic is planned for the next run. Another possible mitigation would be an increase in injection energy (which could be raised to $G\gamma=7.5$).

For the AGS, a new BBQ tune measurement is under development, which can measure the betatron tunes along the ramp continuously and non-destructively.

4.2. Comments

The Committee encourages C-AD to further ramp up simulation efforts, measurement campaigns, and instrumentation upgrades for the AGS, following the successful improvements at RHIC. Many technical developments for RHIC (e.g. feedback systems) could also be implemented on the AGS. The committee supports the planned upgrade of AGS beam diagnostics, in particular turn-by-turn profile measurements for injection matching, continuous tune measurements, and an intensity-independent polarimeter.

The most important issues for operating the AGS with high-intensity polarized-proton beams are the emittance growth at injection, the apparent loss of polarization at high intensity, and the mitigation of expected SC effects. Points of concern are the lack of an optics model at injection, missing diagnostics and incomplete beam control.

A polarisation budget from the source to collisions in RHIC would underline the priorities taken and to be taken. The expected polarization from the AGS with the new enhanced source current and different collimation conditions (beam emittance and intensities) in the booster was not clearly shown.

The planned intensity increase may move the AGS operation into a space charge affected regime. A tune shift in the region of -0.2 may create severe resonance driven effects, especially under the presence of synchrotron motion (trapping). A dual harmonic operation of the RF systems could be considered to compensate for the enhanced space charge and to eventually relax trapping effects in resonances.

In order to predict beam loss under enhanced space charge conditions, a better understanding of the linear and nonlinear machine properties at injection seems to be required. A modeling by means of a tracking code which includes the magnet imperfections, the longitudinal motion and the space charge would be useful. This would require the availability of measured magnet field data, which may be obtained partially from the existing reference magnets. In parallel to the model development, experimental tune scans may be performed to identify the existence of nonlinear resonances, even at snake operation.

Under the presence of enhanced space-charge tune shift, the large tune motion used for optimized heavy ion operation (in the order of 0.1) could be a concern. Why is this required? How strong is the influence of eddy currents?

There are still discrepancies between ZGOUBI and MAD-X in the presence of snakes. These should be resolved.

4.3. Recommendation

- The polarization loss in the AGS could be measured for a low-intensity large-emittance beam to check the explanation that polarization loss at high intensity is only due to the large amplitude particles and not to other, intensity-dependent phenomena, e.g. space charge or IBS.
- For a better understanding of the origin of the emittance increase after injection into the AGS, we recommend developing and implementing a fast profile diagnostics e.g. IPM or OTR. Collaboration with the GSI, CERN and/or FNAL beam instrumentation teams should be considered. A new fast IPM may also replace the existing IPM in the AGS booster. Thereby, the dependence of the transmission dependence on the beam intensity could be better interpreted.
- An optics model including the cold snake needs to be established and validated with beam measurements at AGS injection.
- Attempt to measure and model emittance-growth patterns in the AGS.

5. High intensity protons in RHIC

5.1. Findings

The RHIC ramp current-transmission efficiency decreases at the highest intensity, with a few percent loss at 2 10^{11} protons per bunch. The losses occur during the final squeeze where particles in the tails are scraped away. The problem appears at high intensity, since beams with higher intensity have larger emittance. There may also be some e-cloud emittance blow up below the instability threshold. With the upgraded source the intensity will be higher for slightly reduced emittance, so that no issues with the current-transmission efficiency are expected.

Contrary to the AGS, in RHIC the measured polarization transmission on the ramp is independent of beam intensity.

Potential intensity limits in RHIC have been reviewed, including radiation-safety envelope, dump performance with increased nearby beam-pipe wall thickness (scattered protons channeling inside the beam pipe), collimation system, RF systems, instabilities, and cryogenic heating due to resistive wall and cryogenic BPM cables. While most systems will permit the foreseen higher intensity, there are a few items for which open questions still need to be clarified.

Primary collimators are located next to the experimental IRs. With continuous collimation on the ramp and thickened beam pipe near the dump, there have been no beam-induced quenches up to 2 10^{11} ppb. The 9-MHz RF is a new system, which is continuously being optimized, Run-11 was the first real run with this system; some modifications are foreseen for Run-12 (e.g. lowering Q from 2400 to 642). The 28MHz RF system requires some further studies for higher intensity (transient beam loading and HOM driven instabilities). Separation of the 197-MHz RF cavities for the two beams will allow for 2 times higher beam intensity.

Instability simulations based on the RHIC impedance model suggest that Q'~9 will be required for 3 10^{11} ppb at injection, compared with Q'~5 at 2 10^{11} ppb. The threshold of electron-cloud related dynamic pressure rise has increased over the years to above 2 10^{11} ppb, probably due to a scrubbing effect.

Resistive-wall heating limits the rms bunch length to 20 cm or higher. At present the bunch length is 60 cm. A cryogenic heat load in the RHIC arcs has only been seen once, during a dedicated scrubbing attempt.

Heating of the cryogenic BPM cable will remain at acceptable levels if an orbit interlock constrains the maximum orbit offset at the BPMs to be smaller than 1 cm.

5.2. Comments

How much the e-cloud contributes to the emittance blow at high intensity is not clear. There is some evidence for scrubbing, even between runs, with intermediate warm ups.

Presently employed multiple RF systems lead to a non-Gaussian, multi-peaked bunch distribution. Heat load calculations could be performed for the real non-Gaussian bunch spectrum. However, the committee notes that, ultimately, reducing the longitudinal emittance and using only the 197MHz system might give a Gaussian distribution.

5.3. Recommendation

- Experimentally benchmark instability simulations at injection for the present RHIC, e.g. the chromaticity Q' required to stabilize the beam at different bunch intensities.
- Complete investigations of intensity limits from 28-MHz and 197-MHz RF systems.
- Understand melting limit of beam dump, and the possible effect of regular beam dumps on the nearby magnet lifetime.

- Proceed with the planned studies of electron-cloud effects at higher intensity using unpolarized proton beams in 2012.
- Similar beam tests with higher-intensity unpolarized beam can also be performed for checking radiation safety aspects, beam dump, RF systems, collimators, instabilities, etc., when the hardware is ready.
- Measure the orbital-amplitude dependence of the polarization more accurately to justify the assumption of a Gaussian dependence.

6. Feedback systems in RHIC

6.1. Findings

Orbit feedback operating with a 1 Hz update rate has been implemented in lieu of conventional orbit steering applied at select times during the acceleration cycle. Interaction with energy feedback was corrected by requiring that the sum of the horizontal corrector dipoles strengths be minimized. Energy feedback now uses information from all arc BPMs in the RHIC rings (compared to two BPMs per ring used previously) to provide a higher precision measurement of the beam's energy deviation.

Significant improvements in the understanding of measurement precision, system indeterminacy, and the correction algorithms have occurred in the past few years. This has led to substantial improvement in the precision of the measurement of the average orbit and has enabled feedback-based correction now at the 20μm level (rms) . The 10Hz fluctuations are now dealt with by a separate correction system discussed in the next section.

By allowing controlled operation at tunes much closer to the 2/3 resonance during the energy ramp, the orbit, energy, tune, and coupling feedback systems have directly benefitted the high energy polarization. The Run-11 polarization transmission efficiency was increased by one quarter compared to Run-9. Systematic polarization loss studies, for example through up-and-down energy ramping experiments, with much better control are now enabled and performed.

6.2. Comments

Orbit, energy, tune, and coupling feedback are simultaneously operating during ramps. Chromaticity feedback is not performed continuously but is periodically activated on demand

RHIC accelerator availability has benefitted from the existence of the new feedbacks, principally by improving the reliability of the energy ramps by eliminating failed ramps and allowing more rapid setups of new beam optics in the rings. Continuing the automation process will improve the reliability still further.

With the orbit and beam-feedback systems, installing a new optics for physics running can now be achieved with only one test ramp.

6.3. Recommendation

- Explore whether there may be benefits to having the chromaticity and other parameters under more regular control during collision running. For example, investigate if correcting the orbit more often or triggered by orbit changes has benefits.

- Because the systems are now developed and performing properly, evaluate whether there are any benefits to deploying the beam feedback systems in the AGS.

7. 10 Hz orbit feedback

7.1. Findings

A global orbit feedback system has been developed to suppress the RHIC 10Hz horizontal fluctuation. The feedback system corrects the global orbit using 36 BPMs and 12 dedicated correctors. This feedback system works very well. The 10Hz fluctuation is suppressed by about a factor 6, from 200μm to 30μm in the arcs and from 1000μm-to150μm at the high beta points. The 10Hz feedback systems contribute substantially to the reduction of the beam loss rate by about 20%. The effect is also seen in experimental background and in an instantaneous luminosity gain of 1.5-2%. It may be of concern that the operating margins in the correctors occasionally come close to corrector limits within factors of two.

7.2. Comments

All relevant problems induced by 10Hz oscillations seem to be mitigated. This system works well, and will contribute to future intensity and polarization improvements.

It may be important to increase operating margins of the feedback system, particularly when operating close to an integer tune.

7.3. Recommendation

- Further analyze the orbit oscillations or the feedback strengths to understand the underlying mechanisms. Singular value decomposition of the orbit vs. time matrix or the corrector strength vs. time matrix may be instrumental.

8. Snake resonances in RHIC

8.1. Findings

Spin-resonance strengths in the RHIC lattice have been calculated, for the nominal lattice model of RHIC. The realistic lattice that includes all errors may produce beta beat, off-momentum vertical closed orbit, vertical dispersion, etc. One should use such a lattice with actual corrector settings to carry out detailed and more realistic simulations.

The basic mechanisms of snake resonances are well studied and measured in RHIC. The collider is operating at a very tight tune space with no room for an enhanced beam-beam tune shift. Since the orbit feedback has accomplished to an rms orbit error of about 20μm, a new operation point near an integer tune has also been contemplated for better collider performance.

8.2. Comments

The machine is tuned for collider experiments and there is not much time for polarization-dynamics studies. The energy of collision may not be at the optimal energy for polarized beam operation. It is not yet known what mechanisms contribute to the polarization lifetime at collision.

8.3. Recommendation

- Resonance strength calculations should incorporate a realistic operational RHIC lattice.
- Use the realistic lattice and the measured closed orbit to find the strengths of depolarizing spin-orbit resonances close to the working point, particularly when it is to be chosen close to an integer. Use two families of correctors to eliminate harmonics in the closed orbit that contribute most to these resonance strengths.

9. Strategy for more polarization

9.1. Findings

In 2010, this committee had recommended to perform more spin-tracking simulation of the accelerator chain. This recommendation has been followed conscientiously. Two tracking programs were improved, compared, and found satisfactory. These were the basis for the presented studies.

It had already been seen that the vertical tune should stay away from the 7/10th depolarizing resonance, and because of improved feedback and beam stability, it was possible to operate closer to the 2/3 resonance, which improved polarization. Tracking studies have now given more insight into the width of this depolarizing resonance. However, this width is still not completely quantitatively modeled. Also other resonances have not been understood in detail, e.g. the 11/16 resonance, originating from orbit distortions and snake errors has different strengths in the two RHIC rings.

An analysis of the amplitude dependent polarization has been pursued with much success, using measurements and a simple, heuristic Gaussian model to follow the core polarization and the average polarization along the accelerator chain. This shows that polarization loss is now mostly produced by nonlinear, intrinsic resonances, which depolarize not the core, but the higher amplitudes of the beam.

We view it as a mayor accomplishment of accelerator operation and stabilization that polarized beams could be decelerated from 250GeV to 100GeV without mayor problems, showing that the polarization loss during acceleration and deceleration is limited.

It was reported that a measurement of the polarization versus the horizontal orbit angle in each snake showed that the snakes are sufficiently aligned with 180 degrees of angle between them. It seems surprising that magnet-alignment after 2 kilometers will be precise enough. A study of the polarization’s sensitivity to the horizontal orbit error could compare the sensitivity of this angle with surveying tolerances. This may yield that the polarization is now high enough and the beam stable enough to repeat this measurement carefully in order to optimize the polarization.

The presented tracking studies have shown that the depolarizing effect of weak resonances is small. However, the understanding of the strongest resonances remains partially qualitative. For example, it is not yet precisely known why the two strongest resonances with about the same strengths lead to very different polarization loss.

The n-axis has been analyzed by accelerating a beam with completely vertical initial polarization. At high energy this showed that approximately 5% of the polarization is lost due to the opening angle of the n-axis alone. However, there are specific energies where the n-axis is rather parallel so that the associated polarization loss would be nearly zero. A fine energy scan would help to find these optimal energies.

9.2. Comments

It is welcome that Tec-X has become involved in spin tracking through BNL, as this will make spin tracking available to a wider community. The performed work is of very high quality, fitting for the leading center of polarization dynamics in the world.

9.3. Recommendation

- Verify by tracking particles with large amplitudes whether Froissart-Stora formula can be used to evaluate depolarization at non-linear resonances.
- Pursue start-to-end simulation with reasonable orbit errors and polarization to quantitatively understand the strongest depolarizing resonances.
- Search for energies where the n-axis is parallel and therefore the polarization highest.
- While there are straight-forward arguments for specific choices of snake angles with 6 snakes in RHIC, it would be worthwhile to make a rigorous study analyzing the performance of other snake choices.
- Include time dependent effects like noise on the orbit to understand the 70-80 hours of depolarization time at high energy.

10. Electron lens predictions

10.1. Findings

The RHIC operation point is restricted between the 7/10th and 2/3rd resonance. Without electron lens compensation the tune footprint will cross one of the above resonance clusters for intensities above 2 10^{11} ppb with a total beam-beam tune shift of DQ = 0.03. Two electron lenses are planned for the operation in RHIC: one for each ring. Two SC solenoids of the e-lens are currently under construction by the BNL superconducting Magnet Division to be installed in the RHIC tunnel in 2012. Additional measures for the luminosity upgrade foresee a reduction of β^* and shortening of bunches for reducing luminosity loss due to the Hourglass effect. For off-momentum particles (half the RF bucket size) the DA (1M turns) with nominal beam-beam strength (N_b = 10^{11} ppb) is only 5.5 sigma (based on element by element tracking). It drops to less than 3 sigma for N_b = 3 10^{11} ppb without e-lens compensation and the beam loss increases for bunches with more beam-beam interactions.

10.2. Comments

- It seems that it has not yet been addressed whether the electron lens operation can affect the proton spin. Studies for electron cooling may be extended to cover this case.
- Another concern is that the presented simulation studies with beam-beam interaction but without noise sources can result in unrealistic estimates for the beam emittance growth.
- The committee suggests to study in more detail the impact of the phase advance between the beam-beam interaction and the electron lens on the overall compensation efficiency.

10.3. Recommendation

- Include noise levels in the emittance growth simulations with beam-beam and evaluate the sensitivity on noise.

11. Electron lens test bench

11.1. Findings

The RHIC electron lens (REL) project is set up in C-AD with the goal of ½-compensation of beam-beam effects in RHIC after intensity upgrades. To assure that all technical issues are properly addressed, a team of scientists and engineers was charged to build a prototype set up of the REL in the EBIS test area. The test bench system will test performance of the main subsystems of the lens: electron gun, HV modulator, collector and beam shape diagnostics. The test stand is being set up at the former EBIS test-stand location, which imposes some slight limitations on the test setup. The main significant differences with respect to the full lens are: (1) The test bench is a straight system, while the lens will have bends; (2) A different SC solenoid is used; (3) The test bench will have no BPMs; (4) DC operation with long (20ms) and short (0.5μs) pulses with a maximum available frequency of 80 kHz (under construction; currently limited to 100Hz). The main components for the test are being either constructed or already tested. Following the conditioning, the electron gun is now ready for operation on the test bench. The test bench is scheduled to start commissioning and tests early in 2012. While the test stand operation does not foresee the installation of BPMs, a design for the BPM system exists and a prototype is available.

11.2. Comments

Having not a bent but instead a straight magnetic system results in impossibility to explore several effects: a) beam transmission efficiency through the bends – used to be of some challenge in other e-lenses; b) secondary electrons and ions dynamics which is very dependent on the bending fields; c) electron beam shape distortions in the bends. The latter effect is the most important one, but simulations show that in the REL, the effect is small. Overall, we believe that bench testing of the straight system is sufficient to explore technical feasibility of the REL.

The committee expresses its concern that the BPM response can vary significantly as a function of the pulse frequency.

11.3. Recommendation

- Perform careful measurements of the REL BPMs: particularly, dependence of their electrical centers' positions and linear coefficients on the signal pulse length (in the range from few ns to few μs).

12. EBIS performance

12.1. Findings

In 2010, RHIC EBIS and all systems making up the new pre-injector have demonstrated reliability and reproducibility in a 38 days NASA research run with various species (He2+, Ne5+, Ar10+, Fe20+, and Ti18+). Reliable production of 1.95e9 Au32+ ions per pulse was demonstrated, too. The strategy to reach the 2012 Run goal of 3.4e9 Au32+/pulse, includes: (1) increase operational electron beam current from 7.4A to 10A; and (2) increase fractional intensity output of Au 32+ ions from 13.5% of total to (design) 18.5%. The electron current increase seems to be straightforward and guaranteed, while improvements in the ion charge state distribution will require serious work on ion injection to increase the intensity of Au1+ into the electron beam.

A number of improvements have been implemented to increase the transfer efficiency in the pre-injector, and the design values of 90% are achieved for EBIS-to-RFQ and RFQ-to-Linac transfers. The EBIS team believes that by using two EBIS pulses per RHIC bunch, the U39+, Au32+ and Cu11+ intensities for the RHIC 2012 are guaranteed.

12.2. Comments

The proposed measures to increase the Au32+ fraction in the EBIS pulse do not seem to fully secure success. So, other possibilities to reach the goal should be carefully considered. For example, it was shown that the peak electron current can be increased from 10A to 12A. Such a 20% gain can provide additional safety margin to reach the 2012 goals. The ion emittance dynamics and budget does not seem to be fully understood and studied presumably because of the lack and difficulty of the beam diagnostics and limited modeling effort. As the result, it was not possible for the committee to evaluate fully whether early charge state separation (before RFQ) can improve the ion intensity in the AGS and RHIC.

12.3. Recommendation

- We recommend to study numerically and experimentally the evolution of the ion emittance in the entire EBIS-based pre-injector chain and explore possibilities for better emittance control/reduction.

13. AGS vacuum failure with Au beam

13.1. Findings

The history of events of damaging of AGS vacuum chambers during Au runs has been summarized. According to the presentation, the link of the damage process to performed beam manipulations (e.g. orbit bumps before extraction) and positions, which are suggested by enhanced beam radii seems obvious. Origin of the destruction is a non-perfect control over the beam position at any time of the machine cycle.

The destruction mechanism is based on a slow radial motion of the beam into the local acceptance-limiting device. In such a beam-loss process the interaction volume is small and suggests under consideration of the relatively small vertical beam size a heating and evaporation of the interaction volume.

13.2. Comments

In order to avoid future damages of the vacuum system, sufficiently thick, local acceptance limiting inserts may be installed without inhibiting the desired beam manipulations (close orbit bump).

Another approach in preventing such destruction processes is assuring a continuous monitoring of the beam position in each lattice cell with introducing a preset tolerance band for the closed orbit excursions. However, detecting relevant position deviations requires an adequate reaction, which should be a fast beam abort process using an internal or external beam dump. Fast beam aboard requires a dedicated full-aperture kicker systems, which should be considered. Alternatively a fast beam abort process may be triggered by beam loss monitors, which than must be installed at all relevant positions.

13.3. Recommendation

- The process of a slow interaction of a radial moving beam with a small surface volume may and should be studied by means of adequate codes considering all relevant and well-known parameters.

14. RHIC off momentum DA

14.1. Findings

The ion-beam operation performance features a re-bucketing of the ion bunches at the beginning of the luminosity fill in order to reduce the bunch length. This procedure implies in turn an increase of the maximum momentum spread in the bunch. Reducing β^* from 0.7 m to lower values in future runs will increases the peak beta-functions inside the triplet to approximately 2km to 3km, resulting in an increase of the chromatic aberrations.

Higher-order chromaticity limits the dynamic aperture for the low beta operation (0.7m) of the RHIC Heavy ion runs. because of the large momentum spread 0.1~0.2%, second and third order chromaticities of several 1000 and several 10^5 respectively give considerable tune shift/spread (~0.01).

The off momentum beta beat is the dominant source of the higher-order chromaticity. The beta beat can be corrected by 24 sextupole families. On momentum beta beat of 15%, corresponding to the existing beta-beat in RHIC, disturbs the estimates for higher-order chromaticities in the model lattice. A beam-based correction method, based on measured beta and the half integer resonance driving terms, is proposed. Sufficient momentum aperture and reduced chromaticity were achieved by the correction in the model simulation.

14.2. Comments

The momentum aperture has been a serious issue in KEKB and SuperKEKB. A model-based correction using many sextupole families has been done with trial and error for both these machines. A comparison of the C-AD approach with this method would be interesting.

The committee was surprised that the bunch re-bucketing is being performed simultaneously with beam-beam interactions. The combined effect of strong non-linearities from the beam-beam interaction and the momentum manipulation might enhance the overall losses.

14.3. Recommendation

- It would be interesting to perform the RF re-bucketing without beam-beam interaction and to compare the resulting beam losses with those of the current operation mode.
- Machine experiments using the sextupole-tuning methods from C-AD and from KEKB should be compared.

15. Scrubbing issues and coating R&D

15.1. Findings

For present RHIC bunch spacing, beam pipes with larger radius in the straight section are more prone to electron cloud than the smaller-aperture vacuum chambers in the arcs. Over the last years, NEG coating in most of the field-free straight-sections has helped to increase the RHIC intensity.

The required e- scrubbing on 316 stainless steel has been measured in collaboration with INFN-LNF for 500-eV electrons. POSINST simulations show that much shorter bunches are required for efficient scrubbing. Taking the integrated electron-cloud heat load as the figure of merit and assuming a heat load determined by the cryogenic cooling limit (2 kW / ring) the scrubbing time required to go from SEY=2.2 to 1.4 is estimated at 50 h.

Short bunches can be produced by injection with “quadrupole-mode pumping” at h=360 and later rebucketing to h=2520, still at injection energy, slowly increasing the RF voltage, while monitoring heat load and vacuum pumps, as well as, possibly, the tune shifts from e- cloud.

An ongoing phase-II SBIR project aims at developing a magnetron-sputtering technique for in-situ copper coating of the arcs (in view of eRHIC), which could also reduce the secondary yield in the arc, either due to the surface roughness of the sputtered copper (10μm thickness) or by additional amorphous-carbon coating. The wall resistivity taking into account a 10μm Co layer has been computed including magneto resistance and anomalous skin effect. It is reduced by much more than a factor 100 compared with the present stainless-steel chamber.

15.2. Comments

In order to benchmark heat-load calculations, it could be tried to measure the resistive-wall heating for the present stainless steel chamber from the cryogenic heat load, e.g. by using the short bunches foreseen for the scrubbing run.

Considerable surface roughness of the sputtered Copper, which is expected to reduce the SEY, might also have an effect on the resistivity. This could be estimated.

The compatibility of the in-situ coating machine with RF fingers and other possible obstacles or discontinuities in the beam pipe should be confirmed. It appears not to be known yet which local electron-cloud heat load could quench a magnet.

15.3. Recommendation

- When evaluating scrubbing scenarios only electrons with energy above about 30 eV will be effective. Therefore, consider the electron energy spectra at the wall when developing scrubbing scenarios.
- Examine the effect of thermal cycling on a sputtered copper layer.

16. Stochastic cooling and booster merge

16.1. Findings

The outstanding developments and history of bunched beam cooling at RHIC has been summarized. As a result of this major effort significant progress has been achieved with respect to various RHIC performance aspects, e.g. 100% increase in the integrated luminosity, suppression of IBS based emittance blow up, suppression of tendencies for coasting-beam production during rebucketing, and reaching the “hard core” limit as equilibrium. A dedicated cooling system for the horizontal plane, based on the technology used for the vertical plane, is in preparation. This new horizontal cooling system which is now being installed in RHIC will reduce the transverse cooling times by a factor of two, for Run-11.

The development of the stochastic cooling systems at BNL came along with major technical developments, like the microwave transmission link enabling highest-frequency, decoupled, interlaced and frequency shifted cooling systems. The stochastic cooling system uses a 700-m microwave link which allowed going to the highest frequency kicker (9 GHz). It is stabilized with an active feedback, using test tones.

A number of further technical improvements and fixations of the existing and running proven systems have been presented, as have been new ideas for further improved pick-up systems, following the highly innovative developments of the past.

Especially problems from the last run (misalignment, bad coax cable, vacuum leak, image current bypass upgrade, replacement of leaking kicker RF feedthroughs) have been addressed.

Aside from the horizontal cooling system, other novelties for 2012 include a two frequency pilot tone for the microwave link stabilization (correcting delay and phase shift).

Ongoing R&D includes a new 180 degree hybrid for the transverse pick up to reduce the wasted power from revolution line, and a new idea for the longitudinal pick up with a good frequency-response performance up to the 12 GHz range. A prototype will be tested at the ATF facility, which can provide the electron beam analogue of a RHIC beam pulse. After successful testing the pickup in RHIC could be replaced by the new design. This would be for Run-13.

The booster manipulation will be changed with the EBIS source. So far the TANDEM pulse (couple of 100μs) was funnelled into a RHIC bunch (longitudinally). With the EBIS, one will inject only 1/2 turn into the booster, and capture this beam with h=4 system (giving 2 bunches). Barrier buckets are used in the booster during the adiabatic capture process in order not to dilute the emittance. Later in the AGS bunches are merged pairwise, namely 16 into 8, and then 8 into 4. By contrast the scheme used so far, with the TANDEM, had included a merging of three bunches into one, which gave rise to longitudinal emittance dilution. With the new scheme there should be less emittance blow up.

16.2. Comments

Considering the aforementioned improvements, the motivation and expected improvements from installing the new horizontal cooling system was not clearly specified. No estimates have been shown.

Faster transverse cooling will increase the longitudinal emittance, which could have undesirable consequences.

The committee is looking forward to the expected test of the new pick-up design which is promising a flat frequency response.

The new stacking concept for the AGS Booster makes use of the lower emittance expected from the EBIS source. However, an integrated calculation showing that the low emittance beam extracted from the source can be maintained through the space charge dominated LEBT and RFQ transport has not been shown. There may be a risk that the expected benefits from the low beam emittances cannot be realized in case the emittance is blown up at the LEBT or RFQ.

The contribution of the off-momentum dynamic aperture to the beam decay rate could be examined/confirmed, e.g. by intentionally degrading the off-momentum optics using the available sextupole knobs.

16.3. Recommendation

- Develop/use model or simulation tools to predict the equilibrium emittances for different cooling rates and intensities, which could be benchmarked against machine observations.
- Try to optimize cooling-rate distributions to optimize luminosity.

17. 56 MHz SRF upgrade and commissioning

17.1. Findings

A ¼ wave superconducting resonator at 56 MHz is being developed and built as an accelerator improvement project. The cavity will be largely beam driven, with an external 1 kW RF source needed for amplitude and phase control. Simulation calculations indicate that a larger RF bucket will result when the cavity is excited to the operating voltage of 2 MV, and this will fight spillage into satellite buckets. The cavity will only be activated after ramping. Cavity fabrication is almost complete; fabrication of other components is just beginning. Current planning has the cavity installed for RHIC Run-14, in a little over two years.

Calculations of mechanical mode frequencies and detuning to pressure fluctuations and Lorentz force have been performed. An HOM damping scheme has been developed based on 4 asymmetric couplers placed of the "short" end of the cavity.

A technical and cost and schedule review of the project including two external and three internal reviewers specializing in RF and SRF was performed in March 2011. Substantial comments on coupler design and cooling and HOM damping were documented and have been addressed in the intervening time.

17.2. Comments

The project reviewers concluded that "the project is on the right track to meeting its scope within cost and schedule". Adjustments to the design mentioned during the presentation to this MAC review do not cause one to rethink this conclusion.

The time for commissioning of the furnace and test with test cavity seems short.

It is unconventional and risky to add the He vessel prior to cold testing. Given this is a new cavity design, and the scheduled milestones are only a few months apart, it is advisable to try to schedule cold testing before attaching the He vessel.

17.3. Recommendation

- Continue addressing the concerns expressed in the March 2011 review.

18. Committee Members of the Machine Advisory Committee

Oliver Brüning (CERN)

Georg Hoffstaetter (Cornell University, Chair)

Geoffrey Krafft (TJNAF)

SY Lee (Indiana University)

Ohmi Kazuhito (KEK)

Vladimir Shiltsev (FNAL)

Peter Spiller (GSI)

Frank Zimmermann (CERN)

19. Agenda

Collider –Accelerator Department Machine Advisory Committee
2-4 November 2011 Meeting

<u>Agenda</u>

Wednesday, 2 November 2011

08:30	Executive session / discussion	
09:00	**Begin of morning session**	
09:00	Welcome (15min)	T. Roser
09:15	RHIC latest performance and upgrades (35+10min)	W. Fischer
10:00	**Coffee break – Small Conference Room**	
10:30	Polarized source upgrade (20+10min)	A. Zelenski
11:00	High intensity protons in Booster and AGS (20+10min)	H. Huang
11:30	High intensity protons in RHIC (20+10min)	C. Montag
12:00	**Lunch – Small Conference Room**	
13:30	Feedback systems in RHIC (20+10min)	M. Minty
14:00	10 Hz orbit feedback (20+10min)	R. Michnoff
14:30	Snake resonances in RHIC (20+10min)	V. Ptitsyn
15:00	Spin tracking and strategy (40+10min)	M. Bai
15:50	**Coffee break – Small Conference Room**	
16:15	Electron lens predictions (20+10min)	Y. Luo
16:45	Electron lens test bench (20+10min)	A. Pikin/X. Gu
17:15	Executive session / requests for additional presentations	
19:00	**Dinner (committee members and presenters)**	

Thursday, 3 November 2011

08:30	Executive session	
9:00	EBIS performance (20+10min)	J. Alessi
9:30	AGS vacuum failure with Au beam (20+10min)	L. Ahrens
10:00	**Coffee break – Small Conference Room**	
10:15	RHIC off momentum DA (20+10min)	Y. Luo
10:45	Scrubbing issues and coating R&D (20+10min)	M. Blaskiewicz11:15
	Stochastic cooling & booster merge (20+10min)	J.M. Brennan
11:45	56 MHz SRF upgrade and commissioning (20+10min)	S. Belomestnykh
12:30	**Lunch – Small Conference Room**	
13:30	Executive session and report writing	

Friday, 4 November 2011

08:30 Executive session and report writing

10:30 Coffee break – Small Conference Room

12:00 Lunch – Small Conference Room

13:00 Close-out